Atmospheric CO_2 Column Measurements from Laser Absorption Lidar Systems

Bing Lin[1], Syed Ismail[1], F. Wallace Harrison[1], Edward Browell[2], Amin Nehrir[1], Jeremy Dobler[3], Byron Meadows[1], Michael Obland[1], Susan Kooi[4], Tai-Fang Fan[4], and

LaRC ASCENDS team

[1]NASA Langley Research Center, Hampton, Virginia
[2]STARSS II Affiliate, Hampton, Virginia
[3]Exelis Inc., Ft. Wayne, IN
[4]Science System and Application, Inc, Hampton, VA

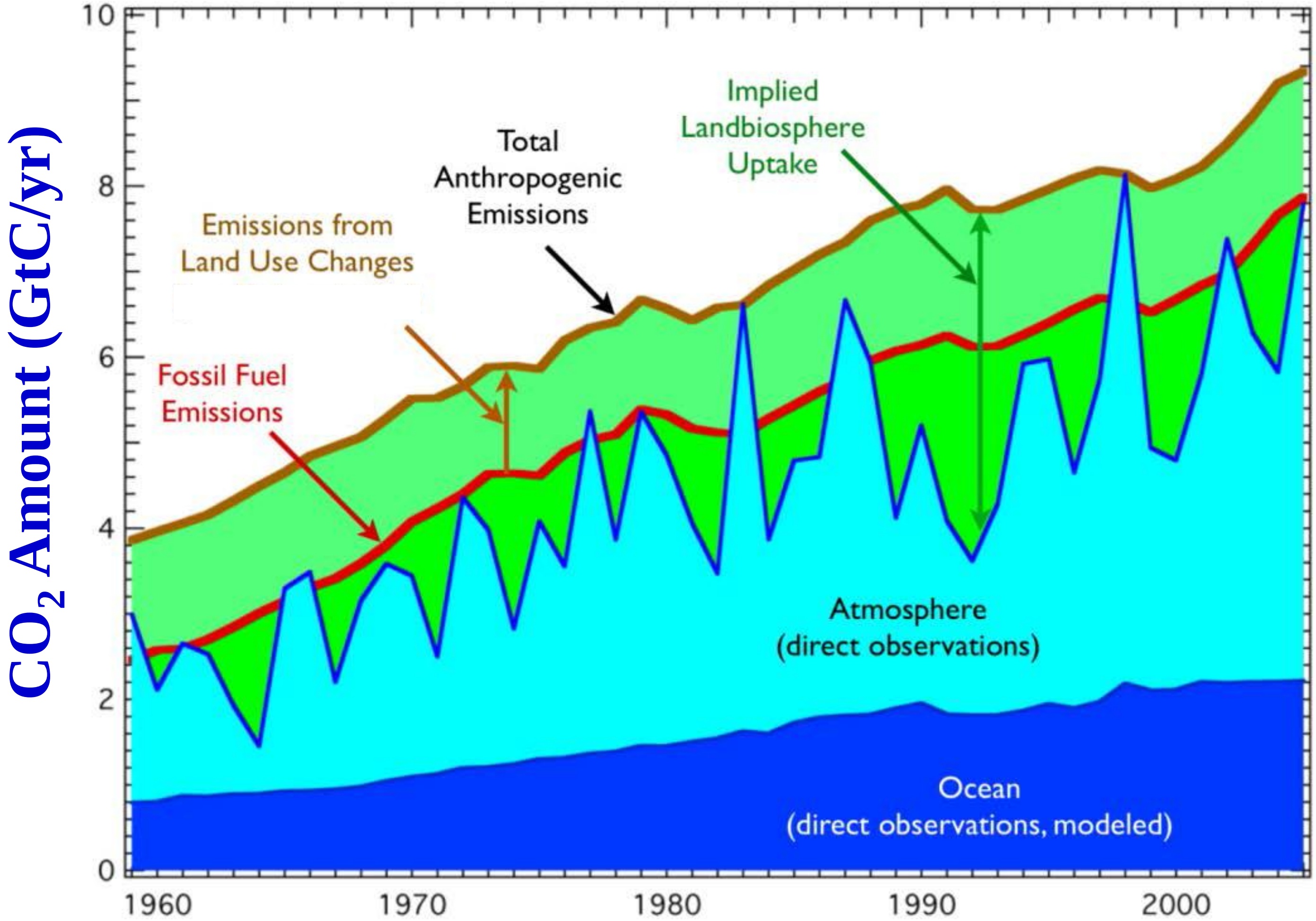
95th AMS Annual Meeting
Phoenix, AZ, 4-8 January 2015

Outline

- **Introduction**
  - **Atmospheric CO_2: missing CO_2?**
  - **Observational challenges**
  - **Approach: active sensing & IPDA**
- **Instrument development**
  - **System design**
  - **Capability: ranging & cloud discrimination**
- **Measurement Results**
  - **Flight campaigns**
  - **Validation**
- **Modeling Efforts**
  - **Improving instrument and space application**
- **Summary**

Annual CO_2 Budget & Variation

Terrestrial sink: residual >>> large errors



Fossil Fuel: 9.1±0.5 ; Land Use: 0.9±0.7

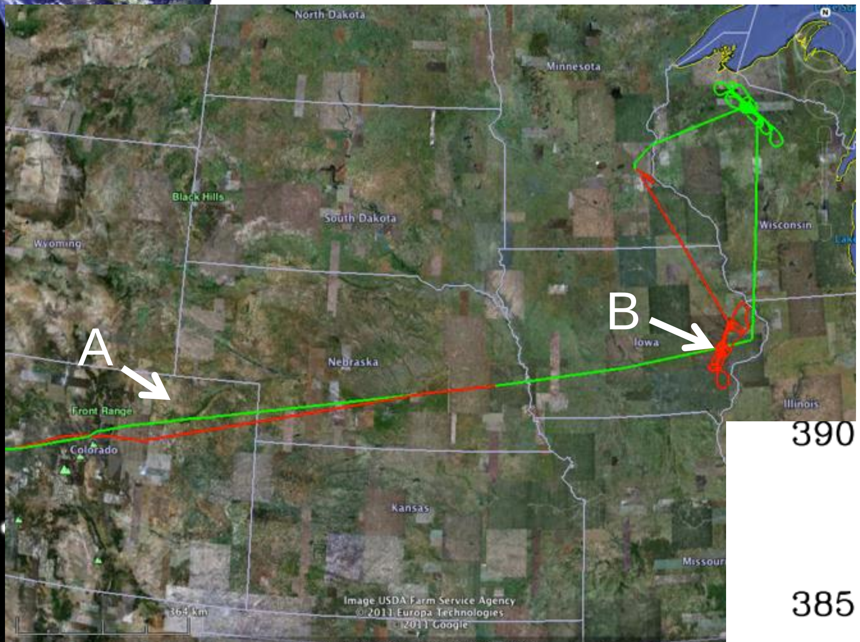
Land Sink: 2.6±1.0; Atmo: 5.0±0.2; Ocean: 2.4±0.5

Land plants and ocean uptake removes some of atmospheric CO_2

Atmosphere CO_2 budgets: large variations

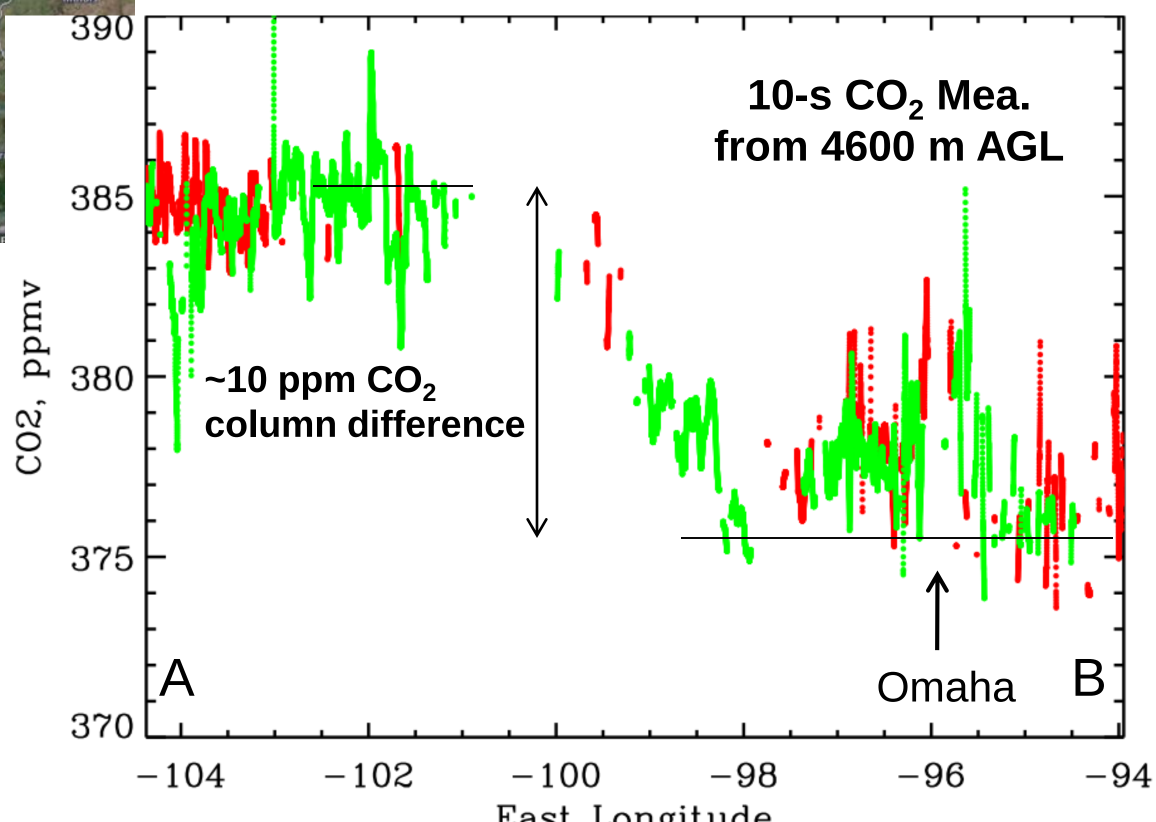
Prediction of this trend and variability, especially in changing climate (?)

Atmospheric CO_2 Measurements



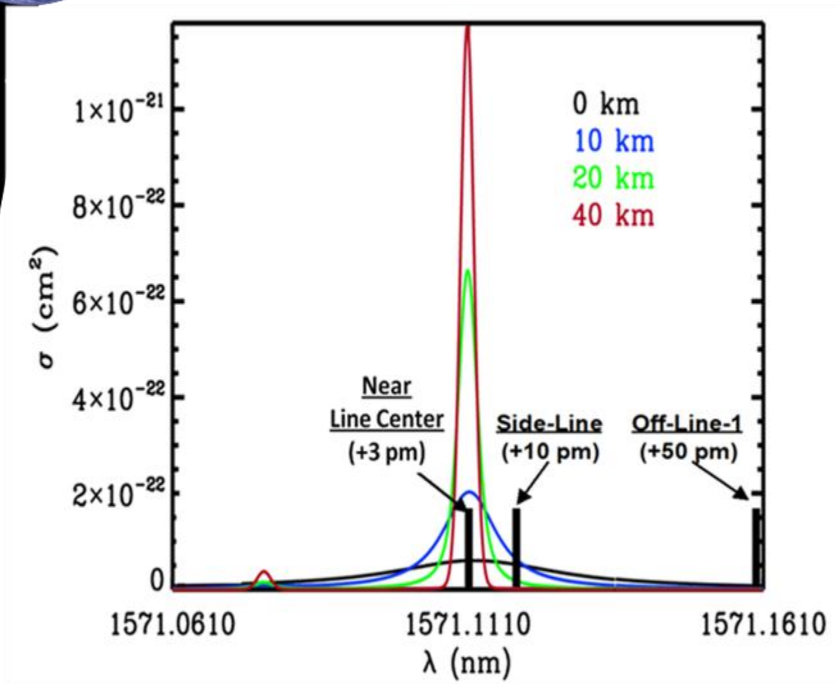
Grand Challenge!

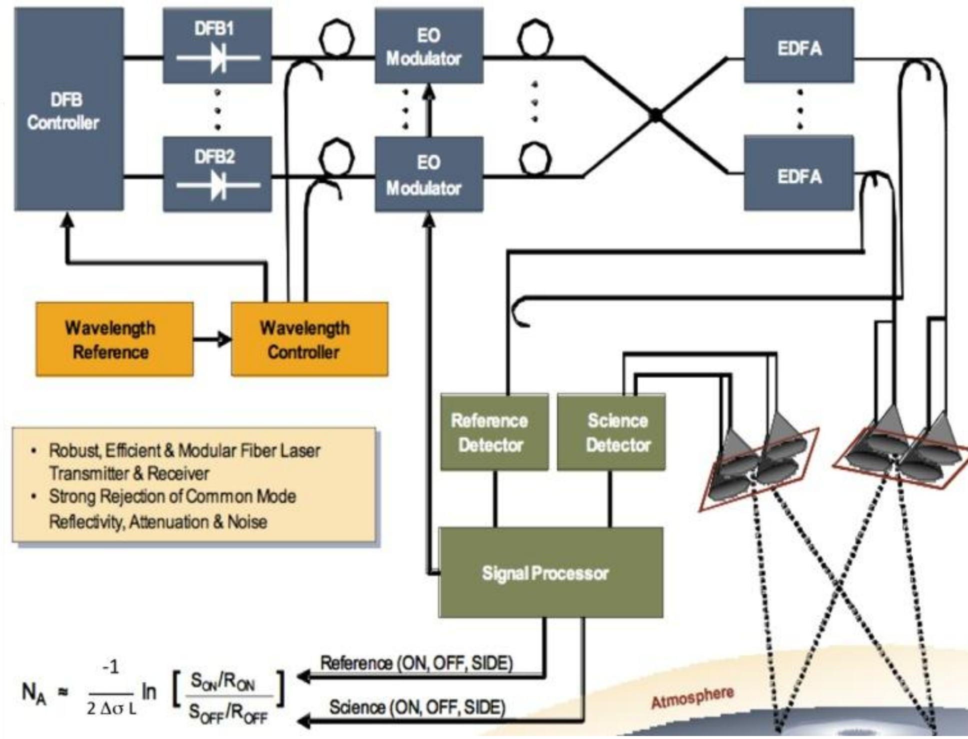
Midwest Flights
Flight 6, 10 August 2011
Flight 7, 11 August 2011



- **CO_2 uptake observed over corn fields in E. Nebraska & Iowa.**
- **Higher CO_2 observed over Colorado & W. Nebraska.**
- **Enhanced CO_2 found in vicinity of Omaha.**

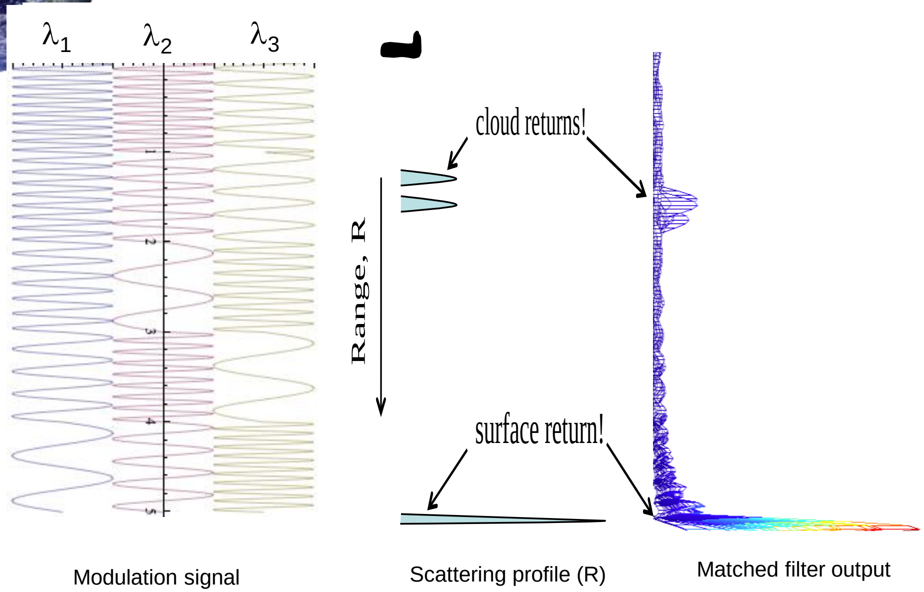
Measurement Architecture





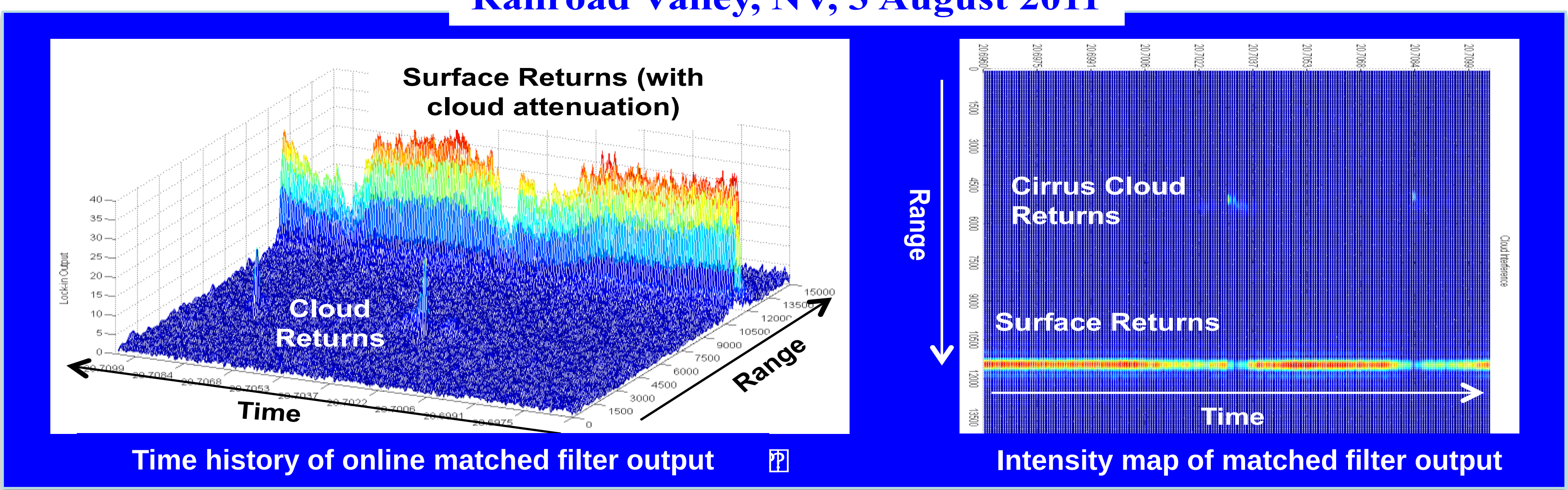
- **Simultaneously transmits λ_{on} and λ_{off} >>> reducing noise from the atmosphere, solar radiation, and surface reflectivity**
- **Separate systems for CO_2 (1.57 µm) & O_2 (1.26 µm) measurements >>> deriving XCO_2 using coincident CO_2 & O_2 column measurements**
- **IM laser wavelengths with unique waveforms >>> range estimation and cloud discrimination (analogous to CW radar and GPS system)**

Intensity Encoding for Ranging and Cloud/Aerosol Discrimination



- Each wavelength encoded with a unique modulation waveform.
- Received IM signals experience certain time delays before reaching the receiver.
- Matched filter is listening and finds the expected waveforms at the time delay corresponding to range, R.

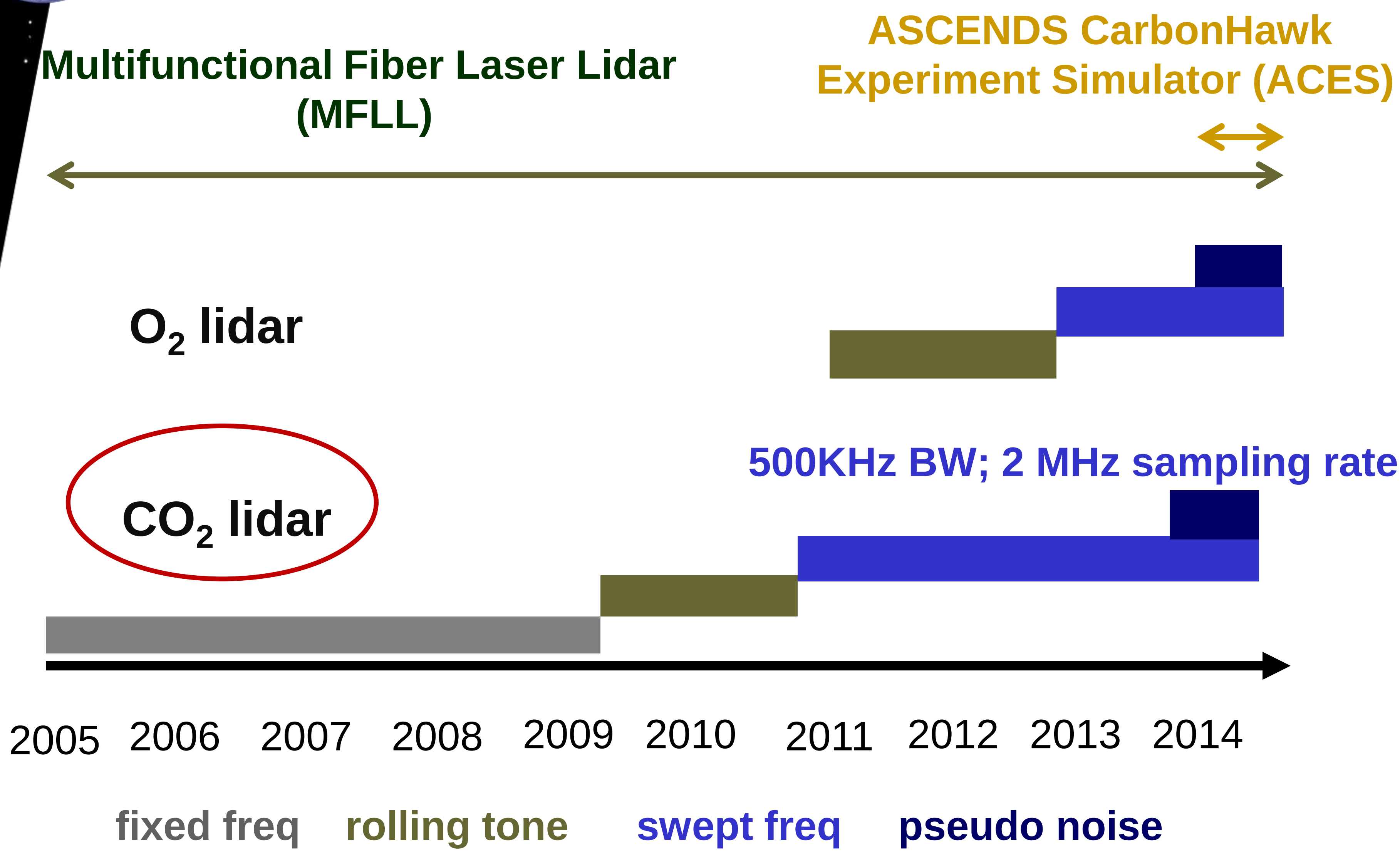
Railroad Valley, NV, 3 August 2011



Time history of online matched filter output

Intensity map of matched filter output

Instrument and Algorithm Development



Instrument Development
(in collaboration with Exelis)

ASCENDS CarbonHawk Experiment Simulator (ACES developed at LaRC with support from Exelis)

Multifunctional Fiber Laser Lidar (MFLL) (developed by Exelis in 2004 Exelis and Langley since 2005)

3×10W amplifier integration

Instrument-aircraft integration

advancing key technologies for spaceborne measurements of CO_2 column mixing ratio

Development and demonstration of MFLL

ASCENDS

21-25 May 2005, Ponca City, OK (DOE ARM)
5 Lear Flts: Land, Day & Night (D&N)

20-26 June 2006, Alpena, MI
6 Lear Flts: Land & Water (L&W), D&N

20-24 October 2006, Portsmouth, NH
4 Lear Flts: L&W, D&N

20-24 May 2007, Newport News, VA
8 Lear Flts: L&W, D&N

17-22 October 2007, Newport News, VA
9 Lear Flts: L&W, D&N, Clear & Cloudy

22 Sept. – 30 Oct. 2008, Newport News, VA
10 UC-12 Flts: L&W, D&N, Rural & Urban

10-16 July 2009, Newport News, VA
5 UC-12 Flts: L&W

31 July – 7 Aug. 2009, Ponca City, OK
5 UC-12 Flts: L&W, D&N

10-20 May 2010, Hampton, VA
6 UC-12 Flts: L&W, D&N

5-11 May 2011, Hampton, VA
5 UC-12 Flts: L&W, D&N, Clear and Cloudy

6-18 July 2010, Palmdale CA
6 DC-8 Flts: L&W, D

28 July – 11 Aug. 2011, Palmdale CA
8 DC-8 Flts: L&W, D

February 19 – March 9, 2013, Palmdale CA
7 DC-8 Flts: L&W, D&N

August 13 – September 3, 2014, Palmdale CA
5 DC-8 Flts: L&W, D

MFLL on Lear-25

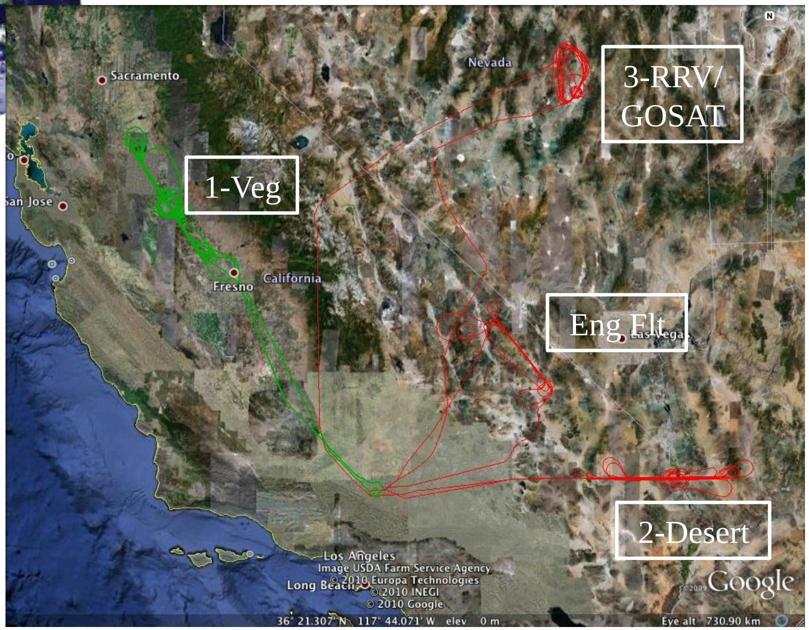
MFLL on UC-12

MFLL on DC-8

various lab, ground range, and flight tests

Finished all data processing of flight measurements!

2010 ASCENDS DC-8 Campaign, 6-18 July

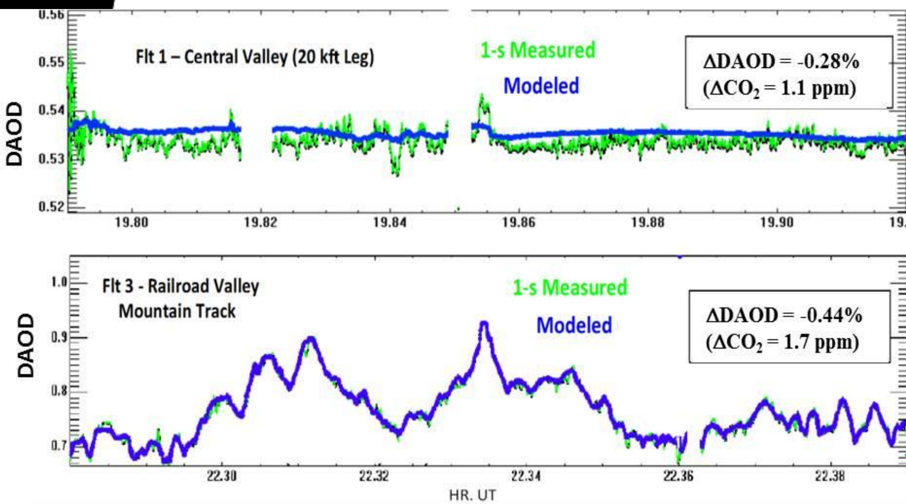


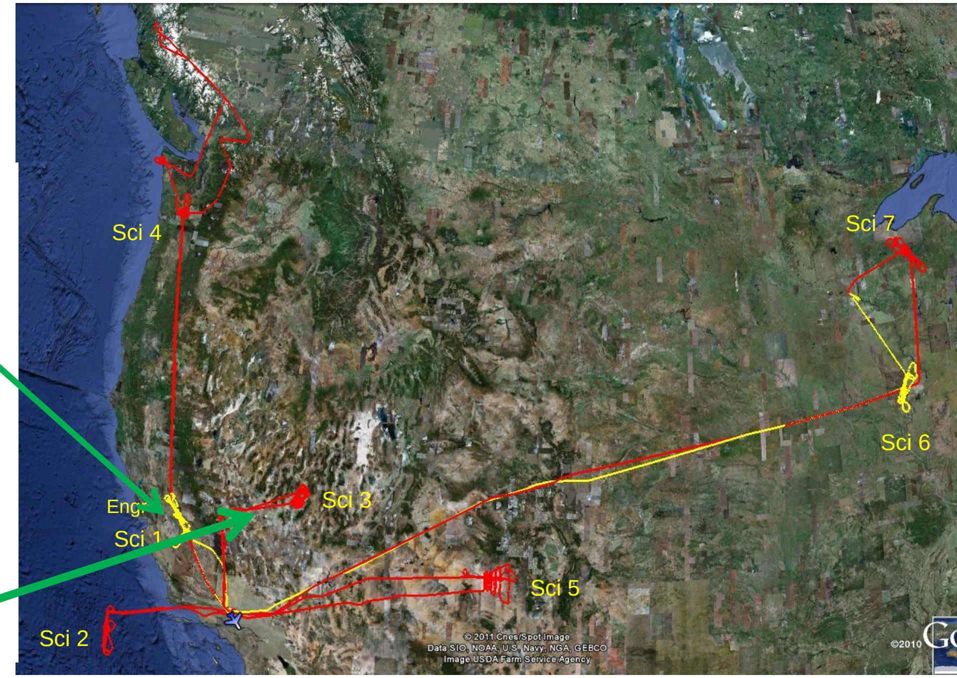
Surface Reflectances & CO_2 Measurement Precision (7-km AGL)

Surfaces	Desert	Desert	Vegetation	Vegetation	Ocean
Location	Railroad Valley, NV	Needles, CA	Central Valley, CA	DOE ARM, Lamont, OK	Pacific off Baja
Median Surface Reflectance [sr^{-1}]	0.143	0.118	0.098	0.080	0.03-0.06
1-s CO_2 SNR (CO_2 [ppmv])	630 (0.59)	612 (0.59)	545 (0.68)	560 (0.65)	~186 (2.07)
10-s CO_2 SNR (CO_2 [ppmv])	1347 (0.27)	1443 (0.25)	1236 (0.30)	1460 (0.25)	~531 (0.72)

2011 ASCENDS DC-8 Flight Campaign
28 July – 11 August

Differential Absorption Optical Depth (DAOD) Comparisons





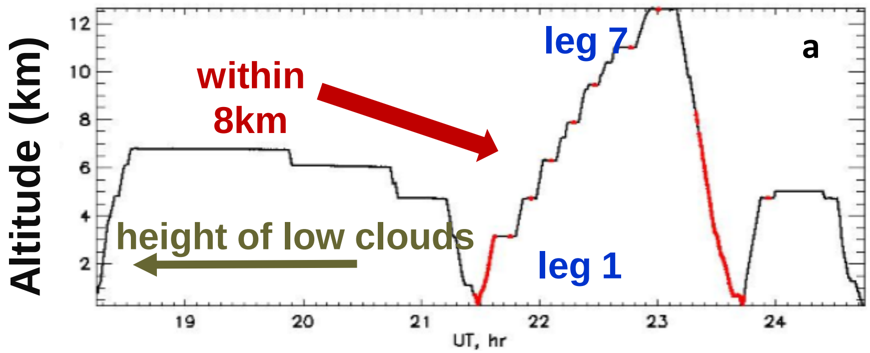
SNR Comparisons

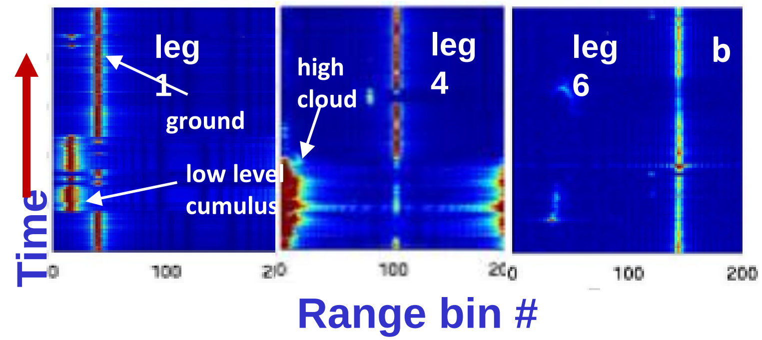
Flight #	Start Hour	End Hour	Delta Time, sec	Nadir Range, m	Optical Depth	CO2, ppmv	1-s SNR	1-s ! , ppmv	10-s SNR	10-s ! , ppmv
1	20.07	20.08	198.0	6406	0.708	389.7	433	0.90	1264	0.31
3	20.03	20.06	211.0	6593	0.755	394.5	517	0.76	1510	0.26
4	15.63	15.70	396.0	6360	0.704	387.1	460	0.84	1325	0.29
5	20.00	20.02	180.0	8063	0.924	391.8	418	0.94	1274	0.31
7	17.21	17.23	79.2	5805	0.632	379.2	396	0.96	1237	0.31

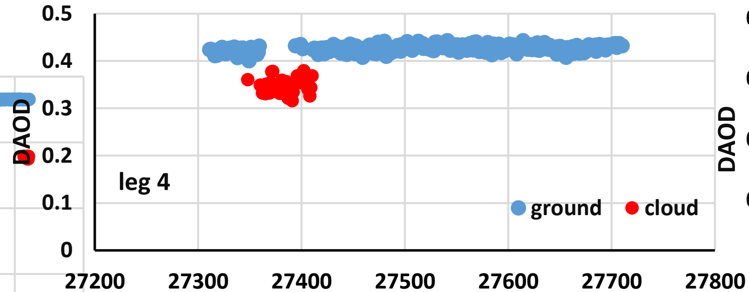
Avg:	6645	0.745	388.5	445	0.88	1322	0.29

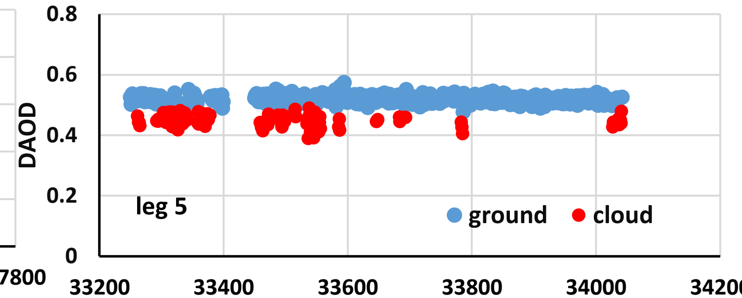
Modeled DAOD: in-situ XCO2 measurements + radiative transfer model to calculate CO2 absorption optical depth

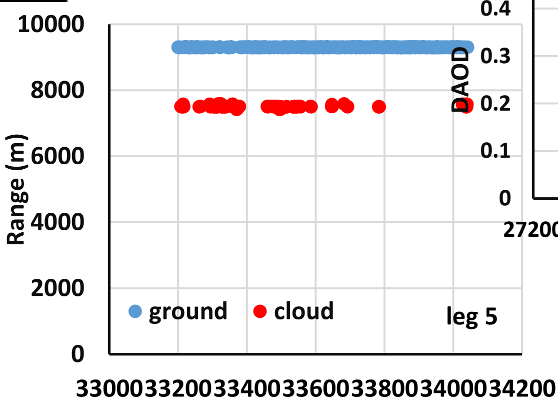
CO_2 Column to Thick Cumulus



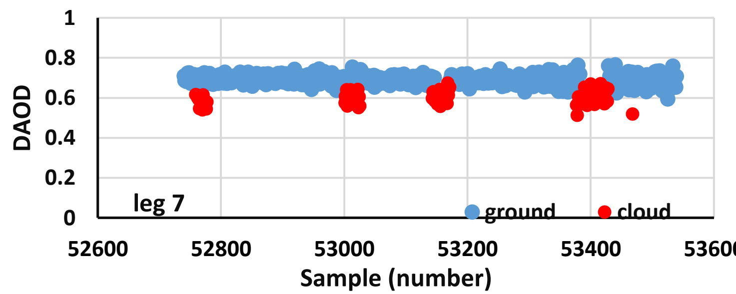


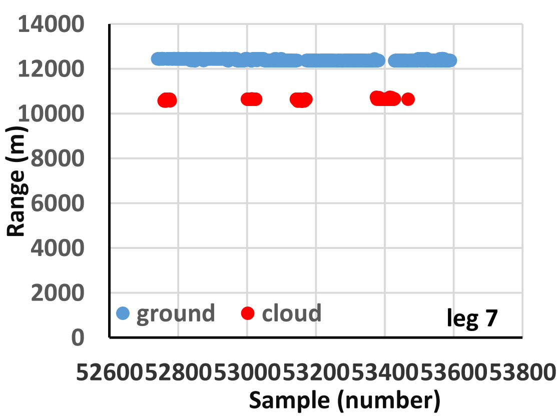






West Branch, Iowa
10-August-2011

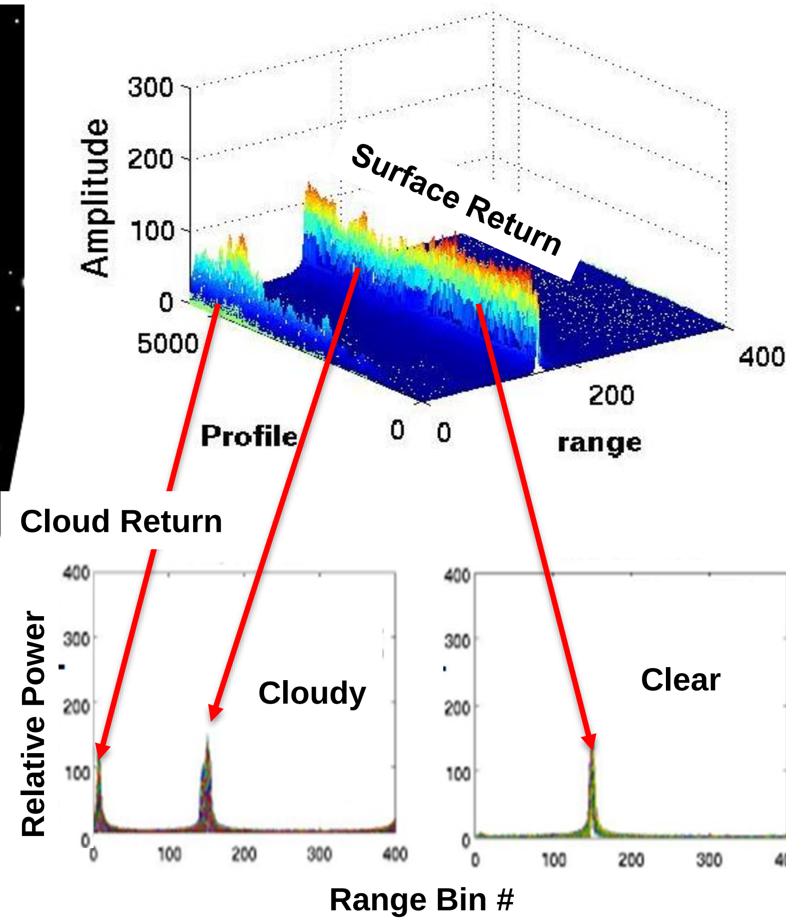


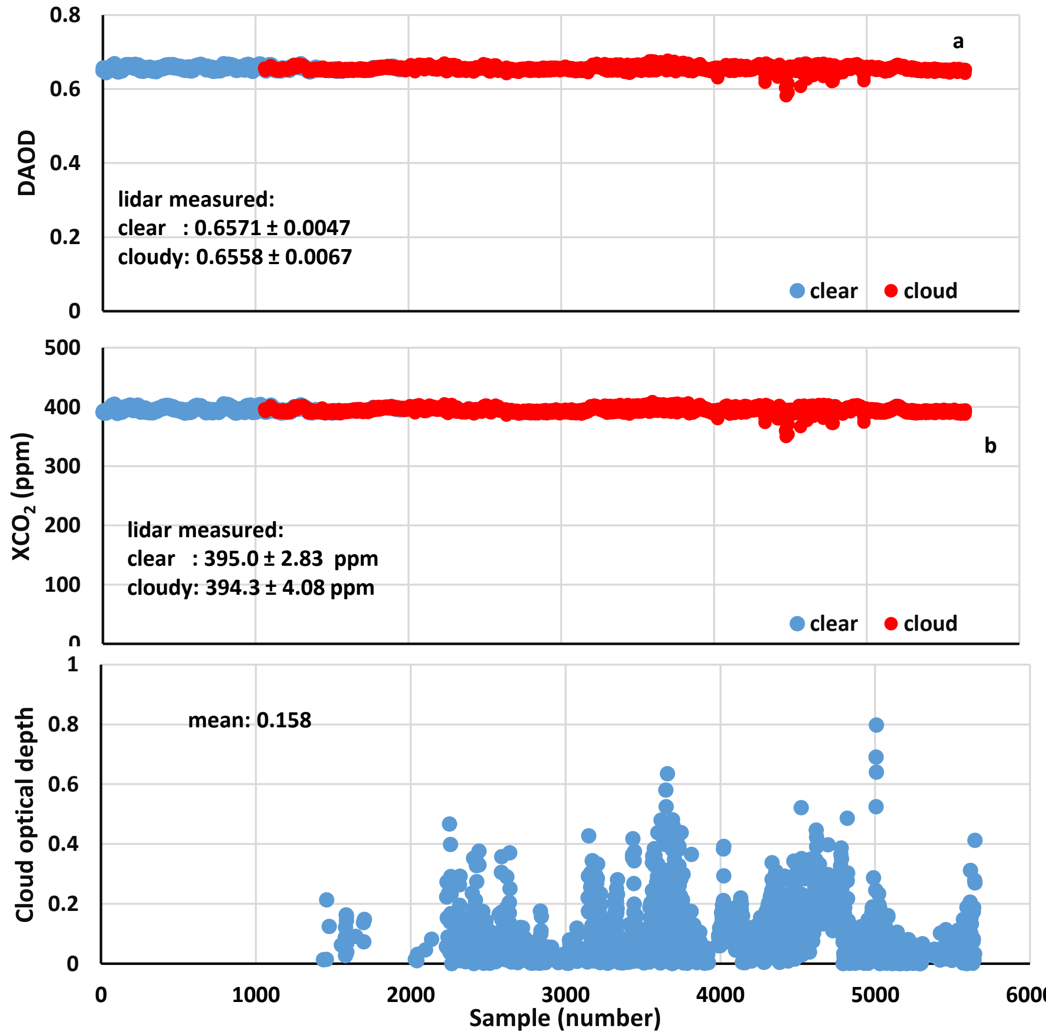


	Leg 4	Leg 5	Leg 7
lidar $DAOD_{ground}$	0.4271 ± 0.0056	0.5196 ± 0.0093	0.6902 ± 0.0155
lidar $DAOD_{cloud}$	0.3480 ± 0.0143	0.4368 ± 0.0243	0.6007 ± 0.0339
In-situ $DAOD_{ground}$	0.4243	0.5160	0.6939
In-situ $DAOD_{cloud}$	0.3417	0.4334	0.6075
lidar $XCO2_{ground}$	383.2 ± 5.02	384.3 ± 6.88	381.6 ± 8.57
lidar $XCO2_{cloud}$	391.5 ± 16.09	387.7 ± 21.31	382.0 ± 21.56
In-situ $XCO2_{ground}$	380.8	381.7	383.8
In-situ $XCO2_{cloud}$	384. 6	384.9	386.4

Lidar CO_2 Column Measurements under Thin Cirrus Conditions (LaRC)

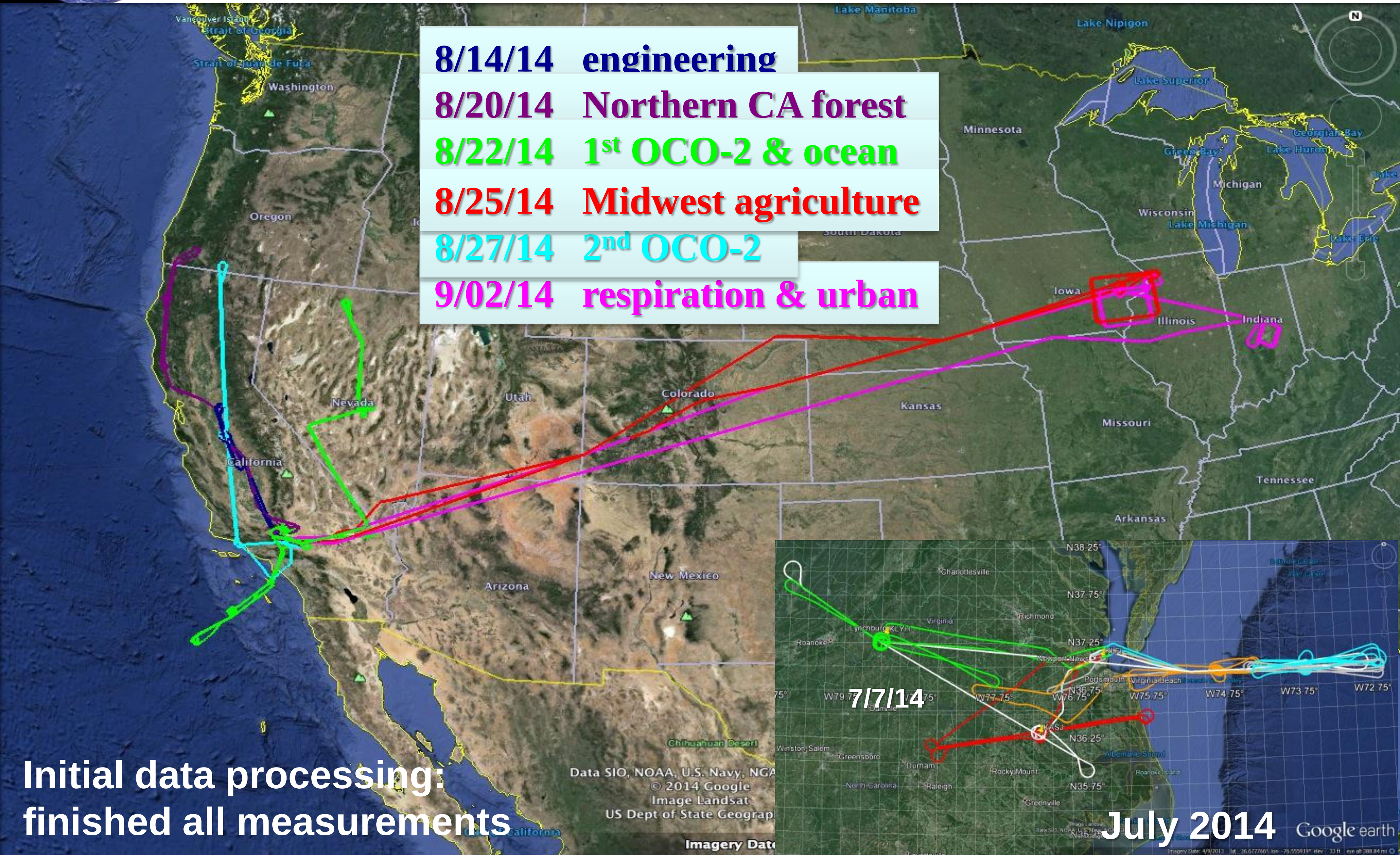
- Data taken over Blythe, CA (Feb. 22, 2013) show consistent CO_2 column measurements as aircraft moves from clear to cloudy areas along a single flight track





2014 ASCENDS DC-8 Campaign & ACES HU-25 Flight Test

8/14/14 engineering
8/20/14 Northern CA forest
8/22/14 1st OCO-2 & ocean
8/25/14 Midwest agriculture
8/27/14 2nd OCO-2
9/02/14 respiration & urban

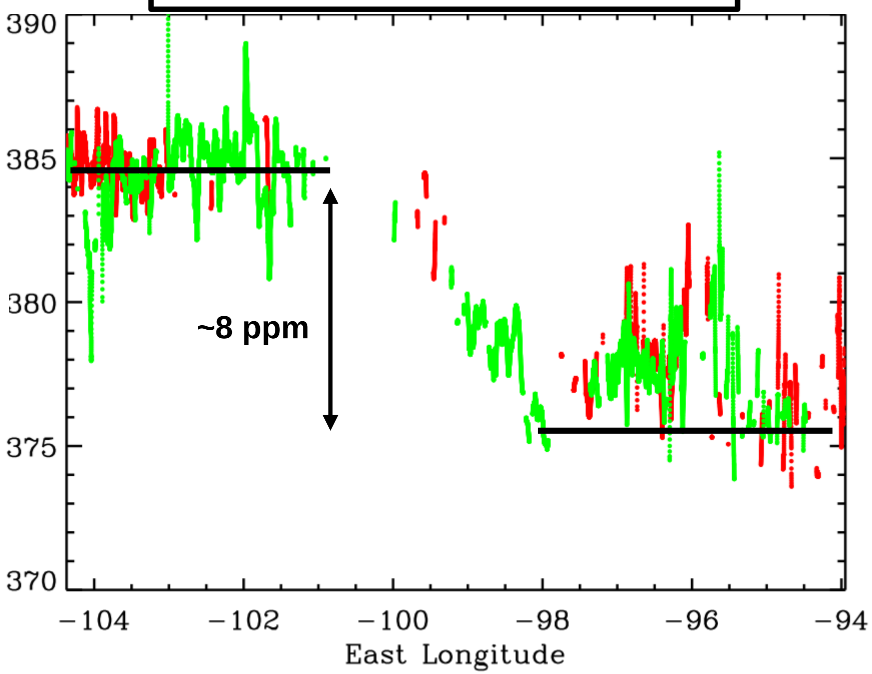


Initial data processing: finished all measurements

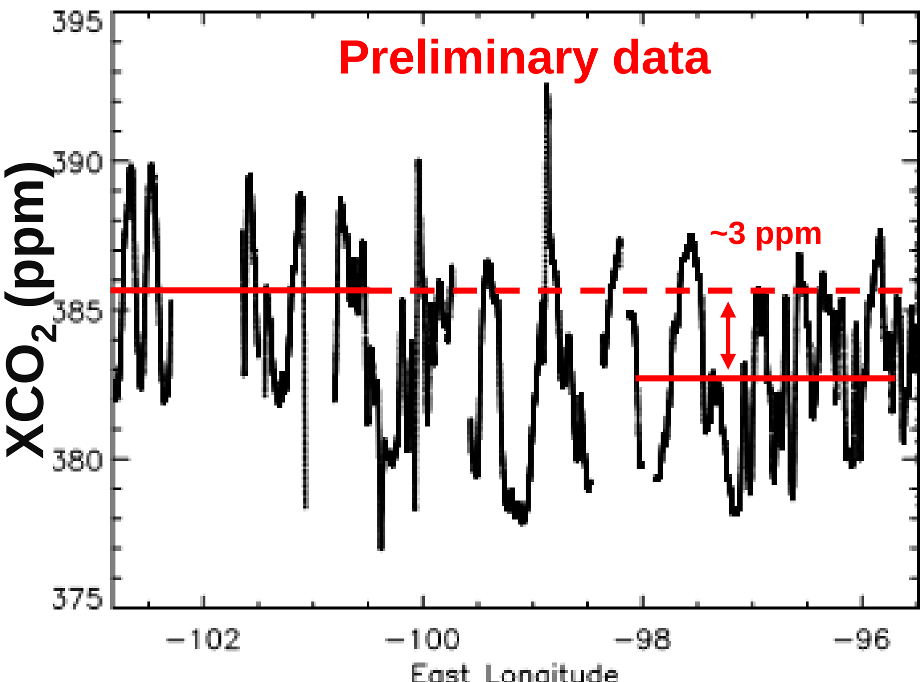
Agricultural CO_2 Drawdown

- Column CO_2 measurements over Midwestern farm fields showed much larger drawdown signal in 2011 (~8 ppm) compared with measurements in 2014 (~3 ppm)
  - Resulting from different meteorological states

2011 Midwest Flights
Flight 6, 10 August
Flight 7, 11 August

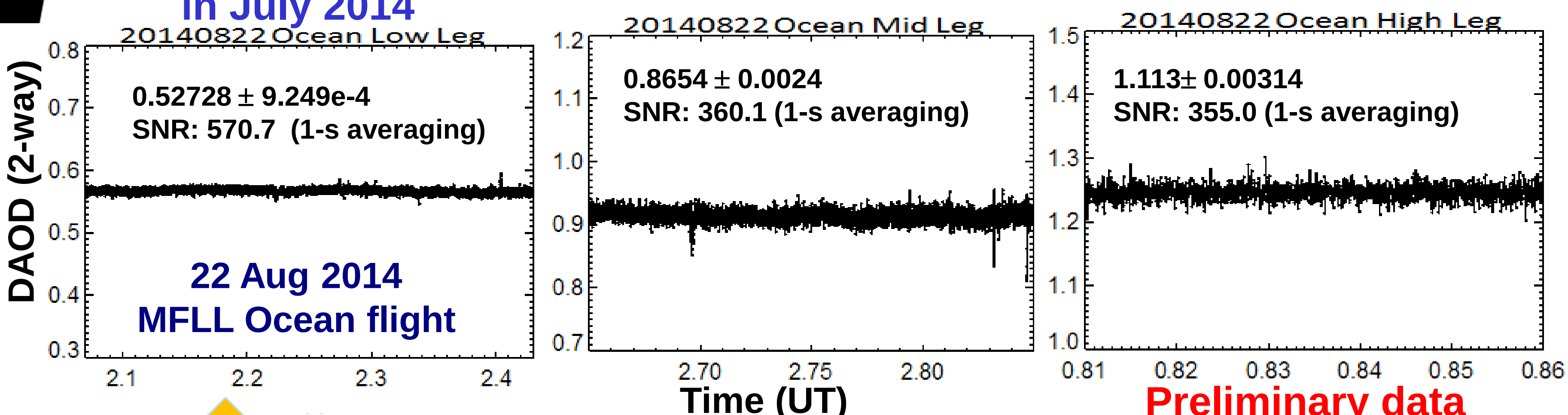


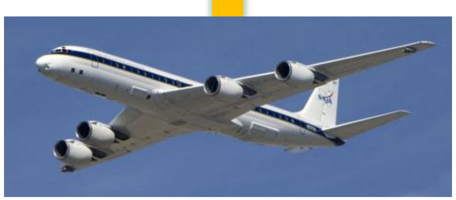
25 August 2014 Midwest Flight



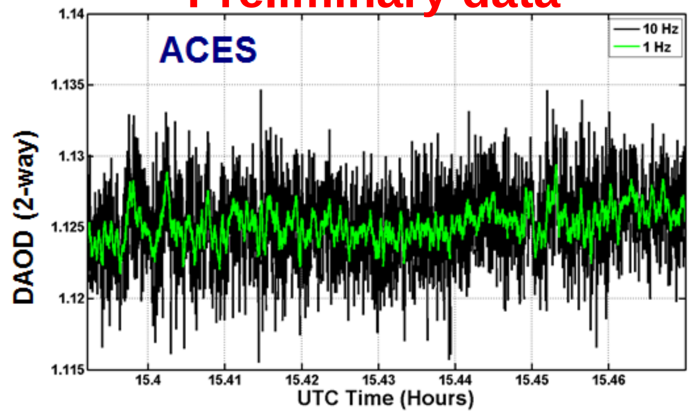
ACES 2014 Flight Campaign

- Flight over the pacific ocean during the 2014 ASCENDS campaign demonstrates the MFLL instrument's high precision measurements over low reflectivity surfaces
- Initial results from the newly developed ACES CO_2/O_2 IPDA instrument (ESTO funded IIP) also show excellent precision over low reflectivity surfaces such as the ocean from 30,000 feet onboard the HU-25 aircraft in July 2014



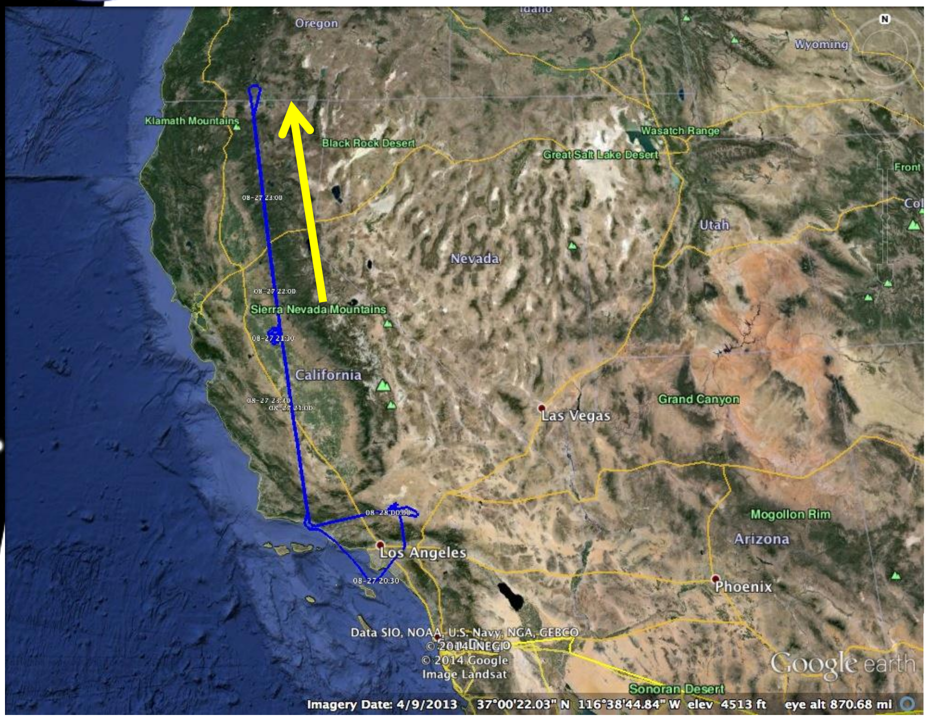


Preliminary data

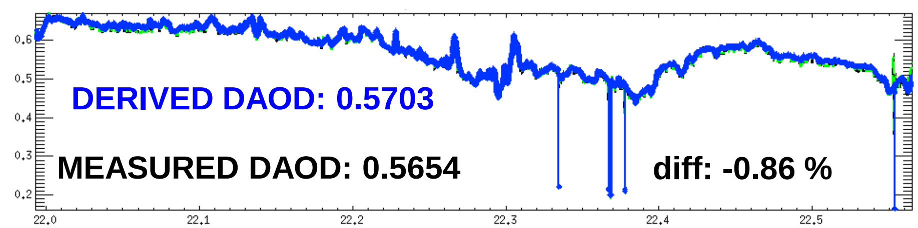


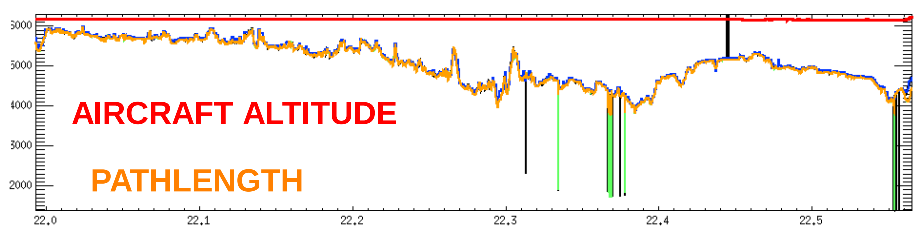
07 Jul 2014 ACES flight over ocean:
SNR = 936 (~0.42 ppmv) for 1-s averaging

OCO-2 Flight: 20140827



- Significant range variability observed over both short and long time scales
- Precise DAOD measurements
- Potentially used in OCO-2 validation, comparison, and evaluation



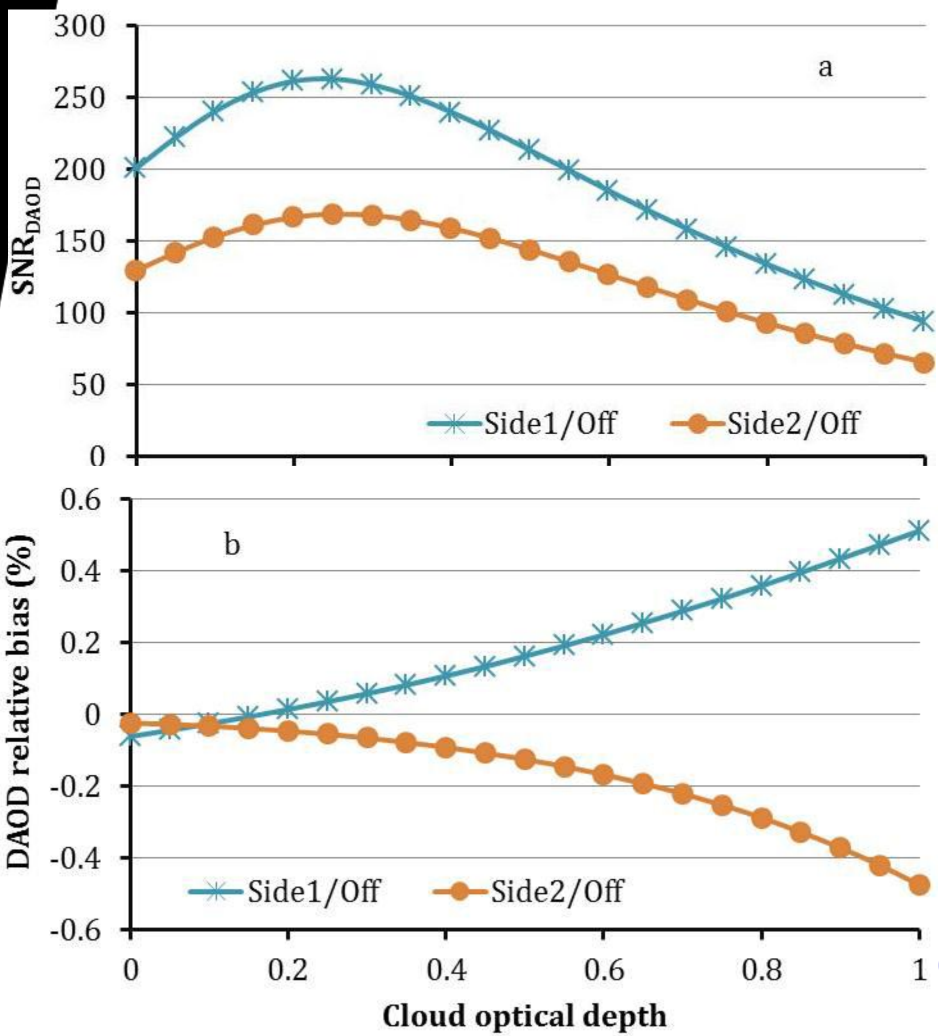


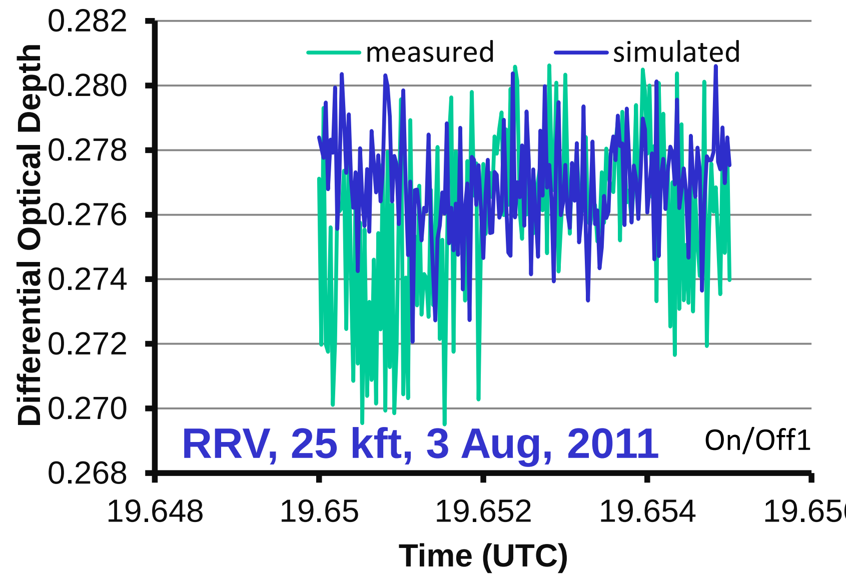
Time (UT)

GPS altitude
GPS – Elevation database
PN range
Attitude corrected PN range
CO_2 lidar pathlength

2012 Modeling of Instrument and Measurement Environment

Science objectives: instrument design and improvement, space applications, CO_2 measurements in various environment conditions





cloud height: 9 km

0.1-s integration time

high SNR & small bias (< 0.25%)
DAOD < ~0.7
dawn/dusk orbit 390 km
(measurement system applicable to 450 km day/night orbits)

Summary

- Global CO_2 observations from space require high accuracy and precision measurements owing very small variations in atmospheric CO_2 mixing ratio.
- LaRC ASCENDS approach: IM-CW IPDA at 1.57μm.
- IM-CW approach has demonstrated the capabilities of CO_2 measurement accuracy and precision as well as of range determination through many airborne flight experiments under variety of environment conditions, including CO_2 column measurements to thick clouds and through thin cirrus clouds to ground for entire atmosphere.
- Technology development/demonstration and space instrument simulation show that this approach can meet the ASCENDS sciences requirements.